APPENDIX 4B. AIRBORNE LIGHT DETECTION AND RANGING SYSTEMS

A4B-1 INTRODUCTION

This Appendix presents the guidelines and specifications that must be used for the application of Airborne LIght Detection And Ranging (LIDAR) systems for gathering the data necessary to create digital elevation models (DEMs) for hydraulic modeling of floodplains, digital terrain maps, and other National Flood Insurance Program (NFIP) products. LIDAR systems may not be able to gather all of the data necessary to create those products. Data in areas such as bodies of water or dense forests may not meet the requirements of this appendix. For FEMA products containing such areas, LIDAR data must be supplemented with data acquired by other means. Lesser standards may be applied for hydrologic modeling of watersheds or other studies. This Appendix is intended to benefit:

- FEMA staff in the preparation of Requests for Proposal; review of proposal responses; and review of draft Flood Insurance Studies (FISs), draft Flood Insurance Restudies (RFISs), draft Limited Map Maintenance Program revisions (LMMPs), and other NFIP products; and

- FEMA contractors (i.e., Study Contractors, LIDAR systems subcontractors) in the preparation of draft FISs, draft RFISs, draft LMMPs, and other NFIP products.

A4B-2 LIDAR SYSTEMS DEFINED

For the purposes of this Appendix, LIDAR is defined as an airborne laser system, flown aboard rotary or fixed-wing aircraft, that is used to acquire x, y, and z coordinates of terrain and terrain features that are both manmade and naturally occurring. LIDAR systems consist of an airborne Global Positioning System (GPS) with attendant GPS base station(s), Inertial Measuring Unit (IMU), and light-emitting scanning laser.

The system measures ranges from the scanning laser to terrain surfaces within a scan width beneath the aircraft. The time it takes for the emitted light (LIDAR return) to reach the earth's surface and reflect back to the onboard LIDAR detector is measured to determine the range to ground. Scan widths will vary, depending on mission purpose, weather conditions, desired point density and spacing, and other factors.

The other two components of LIDAR systems are the airborne GPS, which ascertains the in-flight three-dimensional position of the sensor, and the IMU, which delivers precise information about the attitude of the sensor.

A4B-3 GENERAL GUIDELINES FOR USE

Two important factors in the LIDAR system mission planning are the point density of the randomly spaced LIDAR points and the point spacing of the uniformly spaced DEM points derived from the randomly spaced LIDAR returns. The correct point density necessary to accurately represent terrain and terrain features will depend on flight conditions, mission purpose, and required accuracy. As discussed later in this Appendix, DEM point spacing of 5 meters or less and vertical accuracy of 30 centimeters is required.

Flight-path planning is another important factor in the LIDAR system mission. The flight path shall cover the study area satisfactorily including both parallel and enough cross flight lines to eliminate shadowing and allow for proper quality control.

Unlike aerial photogrammetry, LIDAR missions can be flown without regard to sun angle. Flights may take place at night, if conditions otherwise allow.

Elevation and measurement information related to subsurface channel and hydraulic structure geometry must be obtained through the use of other mapping technologies over deep or turbid water. In some instances, shallow water and near-shore coastal surveys can be accomplished using LIDAR systems equipped with lasers operating in portions of the light spectrum that allow transmission through water.

LIDAR system tolerance for inclement weather conditions (e.g., high winds, wet snow, rain, fog, high humidity, low cloud cover) generally is higher than that of other photogrammetric methods. However, such conditions have been known to degrade the accuracy of laser return data. Therefore, the contractor shall generally avoid missions during inclement weather.

High point densities may allow satisfactory data collection in areas of dense foliage. Still, care must be taken in planning missions with regard to both natural (vegetative) and manmade (structure) ground cover. Pulse width, beam divergence, first and last pulse return discrimination, and choice of the post-processing algorithms may all affect the accuracy of LIDAR-derived data in areas of dense foliage.

A4B-4 PERFORMANCE STANDARDS

The appropriate mapping standards in Appendix 4 of these Guidelines shall apply to NFIP maps and map products derived from LIDAR systems. LIDAR-derived data must have the accuracy required to produce topographic maps and products that meet the National Standard for Spatial Data Accuracy (NSSDA).

FEMA is not aware of any existing LIDAR system performance standards. Current information about LIDAR systems is available from the National Oceanic and Atmospheric Administration (NOAA), National Aeronautic and Space Administration, U.S. Army Corps of Engineers, LIDAR system manufacturers and venders, and private firms that provide LIDAR system services. As professional or trade associations issue specifications and standards, FEMA may adopt them and amend this Appendix.

A. Performance Standards

The contractor must furnish all necessary materials and equipment. The contractor also must supply the supervisory, professional, and technical services personnel required to manage, survey, document, and process all data associated with LIDAR system mapping, scanning, and digital image processing. All deliverables must be provided in accordance with the contract and the requirements in this Appendix.

For the purposes of this Appendix, areas not within two times the DEM posting of data points are data voids. Except within bodies of water and areas recently (no longer than 24 hours) covered with asphalt, raw data voids cannot exceed 5 percent of the collected area. DEM posting shall be the minimum allowed by the data and shall not exceed 5 meters. Vertical accuracy shall be 30 centimeters (see Section A4B-7).

Artifacts are regions of anomalous elevations or oscillations and ripples within the DEM data resulting from systematic errors or environmental conditions. They may result from malfunctioning sensors, poorly calibrated instrumentation, adverse atmospheric conditions, or processing errors. When present, the contractor shall provide an analysis of the effects of the artifacts on DEM accuracy. The analysis shall include a description of the causes (contributing sources) of the artifacts and a description of the steps taken to eliminate them.

B. System Calibration

LIDAR system components are most effectively tested and calibrated by the equipment manufacturer. Therefore, the contractor must provide FEMA with evidence of manufacturer calibration.

In addition to evidence of manufacturer calibration of system components, the contractor must submit evidence that the total LIDAR system was calibrated prior to project initiation for the purposes of identifying and correcting systematic errors. Proper system calibration requires repetitive overflight of terrain features of known and documented size and elevation using flight paths similar to those that will be used in the study area.

C. Flight Planning

Planning a flight path that considers all aspects of data collection is critical to the success of the mission. An analysis of the project area, project requirements, topography, proximity to restricted air space, and other factors will determine the flight path configuration. The mission should include parallel flight lines and, for quality control purposes, at least one cross flight line. The spacing between the flight lines will depend on the desired amount of sidelap between swaths and the terrain.

The density and accuracy of data generated by different equipment vary widely. The contractor shall have the flexibility of providing a flight path to create the necessary point density to meet the posting and accuracy requirements and minimize the occurrence of data voids.

The contractor must check the Position Dilution of Precision (PDOP) in the study area. The PDOP is an indicator of the positional accuracy that can be derived from the current GPS satellite geometry, which varies continuously; the smaller the PDOP number, the higher the data quality.

The contractor must document mission date, time, flight altitude, airspeed, scan angle, scan rate, laser pulse rates, and other information deemed pertinent. For a sample mission data recordation checklist, refer to Table A4B-1 at the end of this Appendix.

D. GPS Base Stations

The contractor must select the GPS base station(s) carefully to ensure reliable differential processing of airborne GPS data. The National Geodetic Survey (NGS) recommends the simultaneous use of two GPS base stations during the mission. (Note: Either public- or private-domain GPS base stations are suitable for use for this purpose.) Where possible, GPS base stations shall have ellipsoid height to an accuracy of 2 centimeters relative to the Continuously Operating Reference Stations (CORS) or the High Accuracy Reference Network (HARN). The contractor must use a high-quality, dual-frequency GPS receiver and associated antenna at the GPS base stations.

A4B-5 GPS CONTROL

Part 1, “Reporting Methodology (FGDC-STD-007.1),” and Part 2, “Standards for Geodetic Networks (FGDC-STD-007.2)," of the *Geospatial Positioning Accuracy Standards*, published by the FGDC in 1998, provide a common methodology for determining and reporting the accuracy of horizontal and vertical coordinates for geodetic control points (survey monuments). Additional guidance is included in NOAA Technical Memorandum NOS NGS-58, “Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm),” dated November 1997. The GPS control guidance in FGDC-STD-007.1 and FGDC-STD-007.2 and in Appendix 4 of these Guidelines shall apply to LIDAR-derived data submitted to FEMA.

A4B-6 POST-PROCESSING OF DATA

For hydraulic modeling, the contractor must provide high-resolution, high-accuracy, “bare-earth” ground elevation data. To restrict data to ground elevations only, the contractor must remove elevation points on bridges, buildings, and other structures and on vegetation from the LIDAR-derived data. In addition to randomly spaced LIDAR points, before and after removal of data associated with structures and vegetation, the contractor must produce a bare-earth DEM, with the minimum regular point spacing, no greater than 5 meters, allowed by the data in eastings and northings. The contractor must use Triangular Irregular Network (TIN) linear interpolation procedures, including breaklines, when validating the vertical accuracy of the DEM.

In addition to DEMs, the contractor shall produce breaklines for stream centerlines, drainage ditches, tops and bottoms of streambanks, ridge lines, road crowns, levees, bulkheads, road/highway embankments, and selected manmade features that constrict or control the flow of water (e.g., curb lines). The contractor shall specify the sources and accuracy of breakline data.

A4B-7 QUALITY CONTROL/QUALITY ASSURANCE

Quality Control/Quality Assurance (QC/QA) of the LIDAR-derived data is primarily the responsibility of the contractor. This QC/QA process shall include reviews of flight alignments and completeness of supporting data (e.g., cross sections, profiles). FEMA or its designee may perform additional QC/QA testing.

NSSDA uses the root mean square error (RMSE) to estimate both horizontal and vertical accuracy. RMSE is the square root of the average of the set of squared differences between dataset coordinate values and coordinate values from an independent source of higher accuracy for identical points. If those differences are normally distributed and average zero, 95 percent of any sufficiently large sample should be less than 1.96 times the RMSE. Therefore 15-centimeter RMSE is often referred to as "30-centimeter accuracy at the 95-percent confidence level." Following that convention, the vertical accuracy of any DEM is defined as 1.96 times the RMSE of linearly interpolated elevations in the DEM, as compared with known elevations from high-accuracy test points.

DEMs should have a maximum RMSE of 15 centimeters, which is roughly equivalent to 1-foot accuracy. The contractor must field verify the vertical accuracy of this DEM to ensure that the 15-centimeter RMSE requirement is satisfied for all major vegetation categories that predominate within the floodplain being studied. The contractor must separately evaluate and report on the DEM accuracy for the main categories of ground cover in the study area. For example:

a) Bare-earth and low grass (plowed fields, lawns, golf courses);

b) High grass and crops (hay fields, corn fields, wheat fields);

c) Brush lands and low trees (chaparrals, mesquite, mangrove swamps);

d) Fully covered by trees (hardwoods, evergreens, mixed forests); and

e) Urban areas (high, dense manmade structures);

f) Sawgrass.

The contractor may further subdivide and expand the above definitions to better accommodate the predominant vegetation types in the study area. The contractor shall evenly distribute sample points throughout each category area being evaluated and not group the sample points in a small subarea.

The RMSE calculated from a sample of test points will not be the RMSE of the DEM. The calculated value may be higher or it may be lower than that of the DEM. Confidence in the calculated value increases with the number of test points. If the errors (lack of accuracy) associated with the DEM are normally distributed and unbiased, the confidence in the calculated RMSE can be determined as a function of sample size. Similarly, the sample RMSE necessary to obtain 95-percent confidence that the DEM RMSE is less than 15 centimeters can also be determined as a function of sample size.

For each major vegetation category, the contractor must test a sample of points and show the test points have an RMSE less than

$$RMSE_{sample} \leq 15\sqrt{\frac{(n-1)-2.326\sqrt{n-1}}{n}}$$

where n is the number of test points in the sample.

The contractor must select a minimum of 20 test points for each major vegetation category identified. Therefore, a minimum of 60 test points must be selected for three (minimum) major vegetation categories, 80 test points for four major categories, and so on. The contractor should consider establishing test points when planning field surveys to gather cross section data for hydraulic modeling.

The contractor shall select the test points carefully in areas of the highest PDOP to evaluate DEM accuracy under trees and in vegetation representative of the study area. Test points on sloping or irregular terrain would be unreasonably affected by the linear interpolation of test points from surrounding DEM points and, therefore, shall not be selected.

Because the definition and criterion for measuring accuracy are derived from the assumption that the test point samples come from a uniformly distributed population with zero mean, the contractor must calculate other statistics. In particular, the mean and the coefficient of skew must be calculated for each sample. Values of the mean of the test points outside of the interval +/- 2 centimeters and/or values of the coefficient of skew outside of the interval +/- 0.5 centimeter may indicate systematic error; the contractor should discuss such values with the FEMA Project Officer (PO).

A4B-8 DELIVERABLES

All data and products associated with contract deliverables must meet or exceed relevant NSSDA and fully comply with the FGDC metadata format standard with the provisions in the contract. The contractor shall use Appendix 7, “Digital Product Delivery Specifications,” of these Guidelines as a guide for preparing and submitting deliverables in digital format.

A. Pre-Project Deliverables

Prior to data collection, the contractor must submit:

1. A map (typically, U.S. Geological Survey maps are desirable for this purpose) showing the study area boundaries and flight path, at a medium scale (1:50,000) or small scale (1:100,000);

2. Documentation specifying altitude, airspeed, scan angle, scan rate, LIDAR pulse rates, and other flight and equipment information deemed appropriate; and

3. A chart of areas of high PDOP, or a list showing the time of the beginning and end of high PDOP.

B. Post-Project Deliverables

Following project completion, the contractor must submit:

1. A LIDAR system data report;

2. A flight report;

3. A ground control report;

4. Data processing procedures for selection of postings, and all orthometric values of x, y, and z coordinates for LIDAR returns. Elevations shall be orthometric heights; and

5. A system calibration report.

The LIDAR system data report must include discussions of: data processing methods used, including the treatment of artifacts; final LIDAR pulse and scan rates; scan angle; capability for multiple returns from single pulses; accuracy and precision of the LIDAR data acquired; accuracy of the topographic surface products; any other data deemed appropriate; and companion imagery, if any.

The flight report must document mission date, time, flight altitude, airspeed, and other information deemed pertinent. The report must include information about GPS-derived flight tracks, provide a detailed description of final flight line parameters and GPS controls (i.e., benchmarks), and include ground truth and complementary reference data.

The ground control report must include, at a minimum, all pertinent base station information and mission notes, including information on GPS station monument names and stability.

C. Delivery of Digital Data

In addition to the pre- and post-project deliverables described above, the contractor must submit the following:

1. All raw datasets, data set of survey points filling voids, data set of transects (if generated), bare-earth DEM data, and breaklines in separate data files; and

2. Uniformly spaced DEM(s), on ISO 9660 standard CD-ROM (or DVD) media in a format specified in Appendix 7 of these Guidelines.

The contractor must deliver raw datasets and LIDAR system data, including orthometric heights for each point, in comma-delimited ASCII files in x, y, and z format. The DEM shall be delivered in Band Interleaved by Line (BIL) format. The contractor also must flag raw datasets from sidelap and overlap areas of separate flight lines. Breaklines must be produced, and breakline files must contain a flag record that identifies them as breakline features and identifies their source and accuracy. The contractor must submit raw datasets in tiles or data models matching those of the DEM.

All deliverables must conform to the projection, datum, and coordinate system specified in the contract. File sizes cannot exceed 1 gigabyte, unless otherwise specified by the FEMA PO. Each file must be organized to facilitate data manipulation and processing.

A4B-9 ACCEPTANCE/REJECTION

The terms of acceptance/rejection in Subsections A4-7.E and A4-7.F of Appendix 4 of these Guidelines shall apply.

A4B-10 REFERENCES

Federal Geographic Data Committee, *Geospatial Positioning Accuracy Standards*, Parts 1, 2, and 3, Final Draft, U.S. Geological Survey, Reston, Virginia,1998.

National Oceanic and Atmospheric Administration, NOAA Technical Memorandum NOS NGS-58, "Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm)," November 1997.

Table A4B-1. LIDAR System Mission Data Collection Checklist	
NOTES	A) Data collection (each flight)
	1. Record flight date and time * 2. Record flight altitude(s) * 3. Record LIDAR system scan angle, scan rates, and pulse rates * 4. Record time LIDAR system receiver is activated/ deactivated * 5. Record all Position Dilution of Precision (PDOP) values * 6. Record height of instrument (before and after flight) 7. Record on-board antenna offsets 8. Note any site obstructions at Global Positioning System (GPS) base station(s) 9. Record airborne and ground-site GPS receivers type and serial numbers 10. Record ground site GPS station monument names and stability *
NOTES	(B) Data handling (each flight)
	1. Record that all files have been labeled correctly and cross indexed 2. Record analyst name(s) responsible for processing and product generation 3. List any auxiliary information used during processing of LIDAR to generate products delivered 4. List major data processing components used

* Denotes Minimum **Required** Information